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WHAT GOES UP MUST COME DOWN: CASSINI MANEUVER EXPERIENCE DURING THE INCLINATION-RAISING PHASE PRIOR TO END OF MISSION

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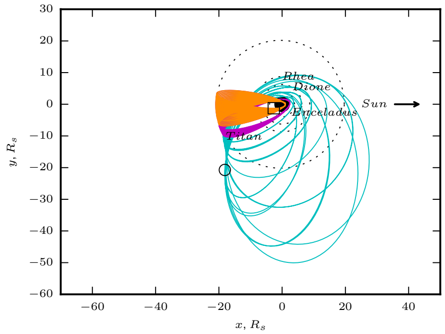
The Cassini spacecraft is kept on its planned reference trajectory using maneuvers designed by the Cassini Maneuver Team. The experiences of the team are documented for 2016—a span of the mission during which the orbit inclination is steadily increasing. This period contains 33 planned maneuvers and 11 Titan flybys leading up to the final orbits before Cassini's plunge into Saturn. Information about each maneuver is provided along with discussion of situations where operations deviated from the normal routine.

INTRODUCTION

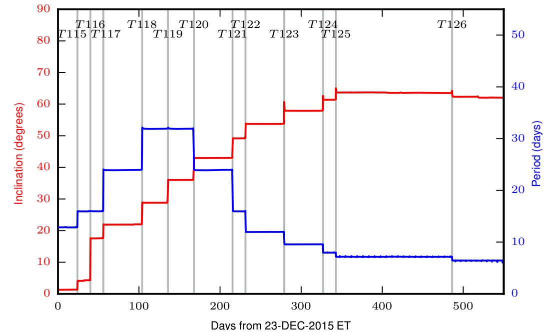
Launched in October 1997, and arriving at Saturn in July 2004, the Cassini spacecraft has been exploring the Saturn system for over 12 years as of this writing. Cassini's many scientific discoveries at Saturn are made possible by a trajectory that has provided scientists unprecedented views of the moons, rings, and planet itself. This trajectory is one of the most complex ever flown by a spacecraft, featuring hundreds of gravity assists and maneuvers throughout its life, and presents a unique challenge to the Cassini navigation team.

The maneuver team, which makes up part of the navigation team, is responsible for keeping Cassini close to its reference trajectory using input from the orbit determination team (OD). Using updates to Cassini's current state and its projected state at some future time, the maneuver team calculates a maneuver (or set of maneuvers) that will bring the future state in line with the reference trajectory at that time.

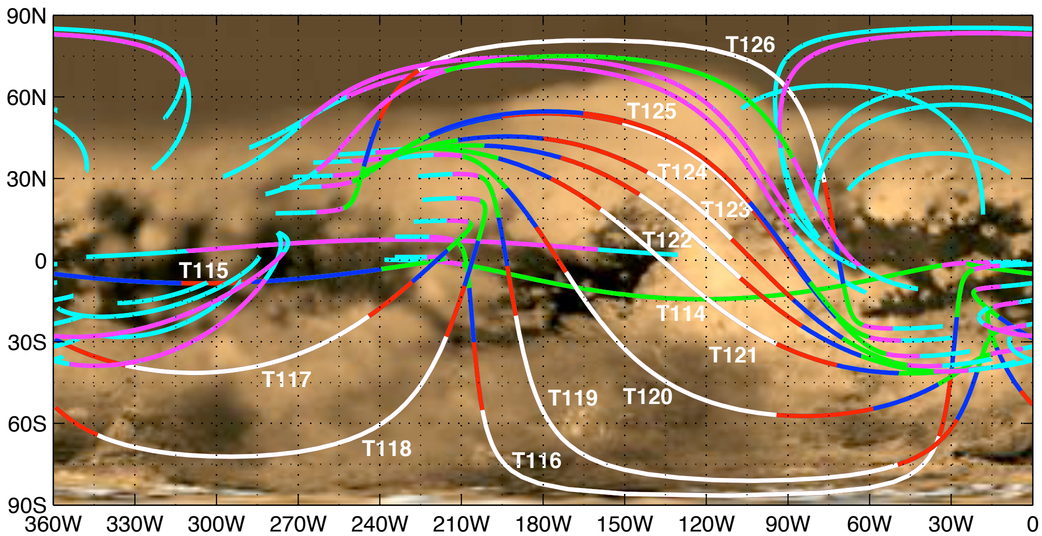
In this overview, we will discuss maneuver design activity for the year 2016, covering orbit trim maneuvers (OTMs) 434 through 468 along with one Enceladus encounter and eleven targeted Titan encounters. Previous years of the maneuver team experience have been documented as well.[1–14] For this portion of the mission, Cassini has been transitioning from an equatorial orbit to a highly inclined orbit using gravity assists from Titan. Having completed this phase, the spacecraft is now in the final stages of its mission, heading towards an impact with Saturn in September 2017.



(a) The Cassini orbit through end-of-mission is shown. The Third Inclination Phase is shown in cyan, the F-ring orbits are shown in magenta, and the final proximal orbits are shown in orange.



(b) Inclination steadily increases during this phase of the mission while period reaches a peak between T118 and T120 before decreasing to its final value.



Altitude

(c) A map showing the flyby ground tracks over Titan for T114 through T126. The shading of the ground tracks indicates the altitude.

Figure 1: Third Inclined Phase of the Solstice Mission.

Third Inclined Phase

The stage of the mission discussed here is called the Third Inclined Phase. During this phase, Cassini's orbit inclination has been steadily increasing from near equatorial to the critical inclination

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of 63.4° after the Titan-125 flyby (T125). At this target inclination, the orbit node crossing distance would remain fixed, which afforded the mission designers great flexibility in designing the final phases of the mission. A plot of the orbit for this part of the mission is shown in Figure 1a. With each Titan flyby, the orbit inclination increases, with the biggest single increase of 13.6° coming at T116.[15] In Figure 1b, the time histories of inclination and orbit period are shown for the rest of the mission.

These high-inclination orbits provided excellent views of the polar regions of both Saturn and Titan. A map showing the ground on Titan covered during these flybys is shown in Figure 1c. T115 was a near equatorial flyby, however T116 had its closest approach over the south polar region at an altitude of 1400 km. T117 flew over the southern mid latitudes, and T118 and T119 again flew over the south polar region, further increasing inclination. The latitude of the subsequent flybys steadily increased, with T125 ending up in the northern mid latitude region. T118 through T121 featured the lowest altitude, with all of them under 1000 km.

MANEUVER STRATEGY

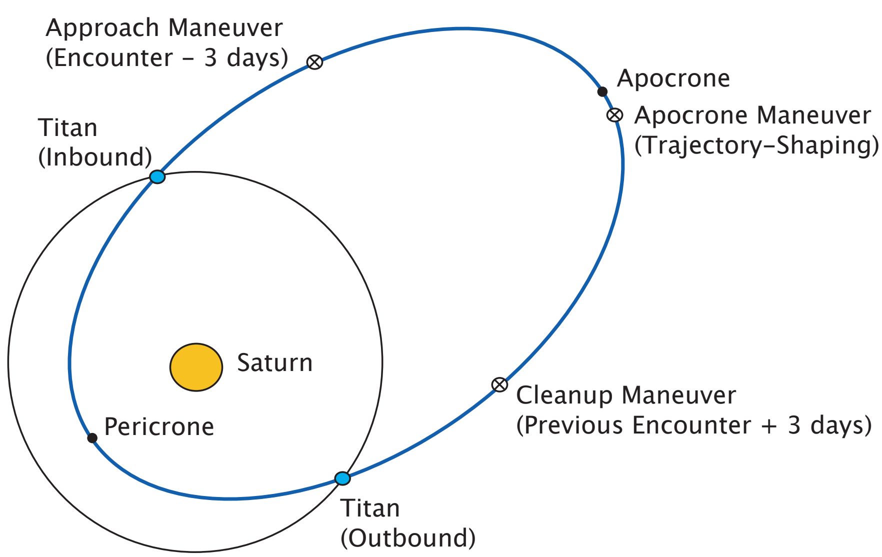


Figure 2: The nominal Cassini maneuver cycle.

Almost all of the ΔV required to fly Cassini on its tour around Saturn comes from Titan gravity assists, which can provide hundreds of meters per second with each encounter. The job of the maneuvers, then, is to keep Cassini on its reference trajectory by tightly controlling the flyby conditions at each encounter. Flyby conditions are specified in terms of B-plane parameters, $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$, and time of closest approach (TCA) to the flyby body. These conditions were determined when the trajectory for the Solstice Mission was designed.[16] The spacecraft is allowed to drift from the reference trajectory between flybys, typically going as far as several hundred kilometers away from its designed orbit during periapsis.

Cassini is nominally controlled using three maneuvers between each moon encounter. A diagram of the Cassini maneuver cycle is shown in Figure 2. The first maneuver after an encounter is the cleanup maneuver, and its purpose is to correct errors in the trajectory resulting from errors in the flyby, with the goal of reducing overall ΔV downstream. Cleanup maneuvers occur three days after a flyby. The second maneuver is the apoapsis (apocrone) maneuver, which usually occurs at apoapsis around Saturn and is designed to target the upcoming flyby. The third maneuver is the approach maneuver, which occurs three days before a flyby. The approach maneuver is a statistical maneuver meant to fix any remaining errors left over from the apoapsis maneuver and further refine the upcoming flyby.

Leading up to each maneuver, the navigation team performs repeated cycles of orbit determination and maneuver design. As the orbit determination becomes increasingly refined with more tracking data, the maneuver is redesigned, and various alternatives are considered by the maneuver team. The possibility of canceling the upcoming maneuver is considered. Canceling a maneuver reduces wear on the spacecraft systems, however the cost of the maneuvers that follow could increase. In addition, the cancellation may result in greater deviations from the reference trajectory. The navigation team takes input from mission scientists to determine whether the deviations will interfere with any science observations. If the ΔV cost is not too great, and the trajectory deviations are acceptable, the maneuver can be canceled.

MANEUVER DATA

Information about each of the maneuvers between E22 and T125 is shown in Table 1. Design ΔV refers to the ΔV intended for the maneuver, and reconstructed ΔV is the actual ΔV achieved as measured using tracking data after the maneuver is executed. Between E22 and T125, 33 maneuvers were planned. Of those, eight were canceled outright, and on four occasions the backup maneuver was executed instead of the prime. Of the 25 maneuvers executed, ten were done with the main engine with the rest being done with the RCS system. In general, a maneuver is performed on the RCS system when doing so on the main engine would result in a burn duration of less than 1.5 seconds. This limitation results in a crossover point of 0.25 m/s as the lower limit for a main engine burn. Additional details about the maneuvers are listed in the appendix in Table 5.

A listing of each of the satellite encounters for the portion of the mission discussed here is shown in Table 2. The flyby targets are shown along with the difference between what was designed and what was actually achieved. In the cases of T123 and T124, the B-plane targets were intentionally shifted because doing so was found to decrease ΔV or reduce deviations from the reference trajectory between encounters. These intentional shifts are noted in parentheses in the last three columns of Table 2. For the T116 and T124 encounters, the time of closest approach was shifted. Shifting TCA is generally done because the approach maneuver would otherwise be too small to implement, yet is still necessary to save downstream ΔV. For the Titan encounters in this phase of the mission, the maximum total miss distance in the B-plane was 2.47 km at T119, while the minimum miss was 0.153 km at T123 (measured from the shifted B-plane point). The average miss for this group of Titan encounters is 929 m with a standard deviation of 774 m.

In Table 3, each encounter span is shown along with the total ΔV for all of the maneuvers executed in the span. The "navigation cost" for each encounter is provided as well, which indicates the difference between the ΔV from the reference trajectory and the ΔV actually spent during the span. The navigation cost is a result of factors such as OD error, maneuver execution error, and maneuver cancellations. For this portion of the mission, the average navigation cost was 0.182 m/s. The maximum cost of 0.6 m/s came between T116 and T117, which corresponds with a relatively large miss of 2.4 km at T116.

Table 1: Maneuver History (OTMs 434–466)

Maneuver	Orbit Location	Maneuver Time (UTC SCET)	True Anomaly (deg)	Central Angle (deg)	Total Design $\Delta\mathbf{V}^*$ Mag. (m/s)	RA (deg)	Dec. (deg)	Total Reconstructed $\Delta\mathbf{V}^*$ Mag. (m/s)	RA (deg)	Dec. (deg)	Burn Type
Enceladus-22 (E22): 19-Dec-2015 17:50:24 ET, Altitude = 5000 km, Flyby ΔV= 0.3 m/s, 27.4 days to T115											
OTM-434	E22+3d	23-Dec-2015 00:29	165.82	707.93	................*CANCELLED*						
OTM-435	~apo	30-Dec-2015 00:00	−159.03	672.78	2.986	346.29	84.66	2.985	346.54	84.70	MEA
OTM-436	T115−3d	12-Jan-2016 23:16	−146.30	299.66	0.036	192.19	6.66	0.037	192.20	6.46	RCS
Titan-115 (T115): 16-Jan-2016 02:21:32 ET, Altitude = 3548 km, Flyby ΔV= 513 m/s, 15.9 days to T116											
OTM-437	T115+3d	18-Jan-2016 23:01	166.46	338.87	................*CANCELLED*						
OTM-438	~apo	23-Jan-2016 22:47	−173.33	318.66	6.847	86.57	79.45	6.844	86.77	79.38	MEA
OTM-439	T116−3d	28-Jan-2016 22:17	−135.84	281.18	................*CANCELLED*						
OTM-439 BU†	T116−2d	29-Jan-2016 22:17	−81.16	226.51	0.016	266.84	−22.84	0.016	266.69	−22.74	RCS
Titan-116 (T116): 01-Feb-2016 01:01:13 ET, Altitude = 1400 km, Flyby ΔV= 774 m/s, 15.9 days to T117, ΔTF = −0.2 sec											
OTM-440	T116+3d	03-Feb-2016 22:03	165.87	337.50	0.583	147.17	−11.97	0.577	146.98	−12.03	MEA
OTM-441	~apo	08-Feb-2016 21:49	−172.63	316.01	0.747	115.49	60.59	0.745	115.68	60.38	MEA
OTM-442	T117−3d	13-Feb-2016 21:34	−131.20	274.58	0.015	34.42	21.03	0.015	34.38	21.04	RCS
Titan-117 (T117): 16-Feb-2016 23:50:49 ET, Altitude = 1018 km, Flyby ΔV= 848 m/s, 47.8 days to T118											
OTM-443	T117+3d	19-Feb-2016 21:05	153.41	693.16	................*CANCELLED*						
OTM-443 BU	T117+4d	20-Feb-2016 21:05	158.52	688.06	0.069	143.47	−33.41	0.068	143.59	−33.64	RCS
OTM-444	~apo	25-Mar-2016 18:55	−167.49	294.00	7.952	114.03	50.73	7.956	113.98	50.67	MEA
OTM-445	T118−3d	01-Apr-2016 18:26	−105.47	232.01	0.063	257.56	1.59	0.063	257.36	1.49	RCS
Titan-118 (T118): 04-Apr-2016 19:43:50 ET, Altitude = 990 km, Flyby ΔV= 856 m/s, 31.9 days to T119											
OTM-446	T118+3d	07-Apr-2016 18:11	142.90	328.74	0.167	173.54	−33.76	0.167	173.84	−33.99	RCS
OTM-447	~apo	22-Apr-2016 17:13	−169.76	281.45	1.767	125.86	31.93	1.762	125.72	31.87	MEA
OTM-448	T119−3d	03-May-2016 16:29	−81.35	193.02	................*CANCELLED*						
OTM-448 BU	T119−2d	04-May-2016 16:29	−0.41	112.05	0.017	348.04	−67.19	0.017	347.48	−67.20	RCS
Titan-119 (T119): 06-May-2016 16:55:45 ET, Altitude = 971 km, Flyby ΔV= 862 m/s, 31.9 days to T120											
OTM-449	T119+3d	09-May-2016 15:59	137.83	324.86	0.551	148.85	−16.05	0.551	148.69	−15.62	MEA
OTM-450	~apo	22-May-2016 15:00	−173.98	276.71	0.026	25.73	26.88	0.027	25.59	27.00	RCS
OTM-451	T120−3d	04-Jun-2016 14:15	−63.01	165.74	................*CANCELLED*						
Titan-120 (T120): 07-Jun-2016 14:07:25 ET, Altitude = 975 km, Flyby ΔV= 862 m/s, 47.8 days to T121											
OTM-452	T120+4d	11-Jun-2016 13:45	149.50	674.44	0.254	301.13	−55.33	0.246	302.06	−55.45	MEA
OTM-453	~apo	17-Jul-2016 11:13	−144.97	248.97	2.025	313.81	9.87	2.021	313.88	9.95	MEA
OTM-454	T121−3d	22-Jul-2016 10:42	−46.61	150.52	0.050	288.77	40.90	0.050	288.36	40.84	RCS
Titan-121 (T121): 25-Jul-2016 09:59:31 ET, Altitude = 976 km, Flyby ΔV= 862 m/s, 15.9 days to T122											
OTM-455	T121+3d	28-Jul-2016 10:27	159.64	320.94	0.184	44.03	45.41	0.185	43.97	45.61	RCS
OTM-456	~apo	02-Aug-2016 10:11	−157.19	277.78	0.794	118.42	4.53	0.793	118.29	4.45	MEA
OTM-457	T122−3d	07-Aug-2016 09:40	−30.76	151.33	................*CANCELLED*						
Titan-122 (T122): 10-Aug-2016 08:32:01 ET, Altitude = 1698 km, Flyby ΔV= 726 m/s, 47.8 days to T123											
OTM-458	T122+4d	14-Aug-2016 09:10	−171.60	1390.59	................*CANCELLED*						
OTM-459	~per	19-Aug-2016 08:54	−24.07	1243.06	................*CANCELLED*						
OTM-459 BU	~per	20-Aug-2016 08:54	76.73	1142.27	0.055	232.73	−71.82	0.056	233.46	−71.78	RCS
OTM-460†, ‡	T123−4d	23-Sep-2016 06:34	−97.27	236.30	0.025	43.84	18.91	*0.024*	*43.65*	*19.04*	RCS
Titan-123 (T123): 27-Sep-2016 04:18:07 ET, Altitude = 1774 km, Flyby ΔV= 714 m/s, 47.8 days to T124, $\Delta(\mathbf{B}\cdot\mathbf{R}, \mathbf{B}\cdot\mathbf{T})$ = (−5.2, +4.4) km											
OTM-461‡	T123+3d	30-Sep-2016 06:03	−167.98	1761.67	................*CANCELLED*						
OTM-462‡	~apo	05-Oct-2016 05:48	119.81	1473.90	0.171	252.69	−59.02	*0.172*	*253.10*	*−58.82*	RCS
OTM-463†, ‡	T124−4d	10-Nov-2016 03:29	−116.34	270.08	0.018	246.58	−54.76	*0.019*	*246.76*	*−54.57*	RCS
Titan-124 (T124): 13-Nov-2016 23:57:03.8 ET, Altitude = 1584 km, Flyby ΔV= 745 m/s, 15.8 days to T125, $\Delta\mathbf{B}\cdot\mathbf{R}$ = −0.8 km, ΔTF = −0.2 sec											
OTM-464‡	T124+3d	17-Nov-2016 03:14	−159.18	683.34	0.143	171.29	−55.70	*0.142*	*171.82*	*−55.87*	RCS
OTM-465‡	~apo	22-Nov-2016 02:59	166.32	357.86	................*CANCELLED*						
OTM-466‡	T125−3d	27-Nov-2016 16:15	90.33	73.93	................*CANCELLED*						
Titan-125 (T125): 29-Nov-2016 22:15:40 ET, Altitude = 3158 km, Flyby ΔV= 551 m/s, 142.3 days to T126											

* Total $\Delta\mathbf{V}$ is the sum of $\Delta\mathbf{V}$s due to the burn, roll and yaw turns, the pointing-bias-fix turn for MEA burns, and the 5.8 mm/s deadband tightening for RCS burns. Expressed in Earth Mean Equator & Equinox of J2000.0 coordinates (EME2000). Mag. = magnitude, RA = right ascension, Dec. = declination.

† Target condition(s) changed via maneuver.

‡ Reported reconstructed ΔV values are based on preliminary OD estimates.

Table 2: Targeted Encounter History (Enceladus-22 to Titan-125)

Encounter	Flyby Characteristics			Reference Trajectory Target Conditions (Earth Mean Orbital Plane & Equinox of J2000.0)				Flyby Differences from Reference Trajectory		
	V_∞ (km/s)	Period (days)	Inc. (deg)	$\mathbf{B}\cdot\mathbf{R}$ (km)	$\mathbf{B}\cdot\mathbf{T}$ (km)	TCA (ET SCET)	Alt.[†] (km)	$\Delta\mathbf{B}\cdot\mathbf{R}$ (km)	$\Delta\mathbf{B}\cdot\mathbf{T}$ (km)	ΔTCA (sec)
Enceladus-22[§]	9.54	12.9	1.3	4902.46	−1871.06	19-Dec-2015 17:50:24	5000	2.80	3.97	0.35
Titan-115	5.45	16.0	2.4	2525.74	5900.66	16-Jan-2016 02:21:32	3548	0.36	−0.43	0.04
Titan-116[‡]	5.42	16.0	16.0	4250.71	−405.23	01-Feb-2016 01:01:13	1400	−1.89	1.46	−0.31 *(−0.2)*
Titan-117	5.43	23.9	20.6	2644.39	2846.56	16-Feb-2016 23:50:49	1018	−0.35	−0.12	−0.02
Titan-118	5.42	31.9	27.8	3613.45	1353.72	04-Apr-2016 19:43:50	990	−0.25	0.34	−0.04
Titan-119	5.41	31.9	35.3	3827.05	−324.53	06-May-2016 16:55:45	971	−2.11	1.30	−0.30
Titan-120[§]	5.40	23.9	42.4	3123.37	−2243.40	07-Jun-2016 14:07:25	975	−0.10	1.10	−0.07
Titan-121	5.40	16.0	48.7	582.50	−3802.45	25-Jul-2016 09:59:31	976	−0.53	0.59	−0.18
Titan-122[§]	5.40	12.0	53.6	−2438.43	−3865.92	10-Aug-2016 08:32:01	1698	−1.19	0.19	−0.15
Titan-123[‡, ¶]	5.40	9.6	57.8	−3688.88	−2826.14	27-Sep-2016 04:18:07	1774	*−5.23* *(−5.2)*	*4.25* *(+4.4)*	*0.03*
Titan-124[‡, ¶]	5.40	8.0	61.4	−4257.76	−1316.21	13-Nov-2016 23:57:04	1584	*−0.86* *(−0.8)*	*−0.38*	*−0.22* *(−0.2)*
Titan-125[§, ¶]	5.39	7.3	63.8	−5865.94	−1414.75	29-Nov-2016 22:15:40	3158	*−0.33*	*−0.13*	*−0.01*

[*] An inbound encounter occurs before pericrone (Saturn periapsis). An outbound flyby occurs after pericrone.
[†] Flyby altitudes not explicitly targeted by maneuvers; reported altitudes from reference trajectory (relative to sphere).
[‡] Target condition(s) changed via maneuver; the quantities in parentheses denote differences from reference trajectory.
[§] Flyby differences may appear large due to cancelled maneuver(s).
[¶] Reported reconstructed ΔV values are based on preliminary OD estimates.

In Table 4, the per flyby navigation costs for Prime Mission, Equinox Mission, and Solstice Mission are summarized. For the entire Solstice Mission, the average navigation cost per flyby is 0.132 m/s—well under the target of 0.3 m/s set for the mission. The navigation costs of the Solstice Mission were lowered because the cost threshold for canceling maneuvers is lower compared to the earlier missions. In other words, maneuvers during the Solstice Mission are only canceled when the cost is around 70 mm/s or less, whereas for the Prime Mission maneuvers were canceled even when the resulting cost in the downstream maneuvers was several meters per second. A plot of the accumulated navigation cost for the entire mission is shown in Figure 3.

Figure 4 shows a diagram of the major events between T115 and T125. The events are ordered by increasing orbit number around Saturn from top to bottom, with the true anomaly of the event indicated by its horizontal position. The period of each orbit is noted along the right-hand side.

MANEUVER DISCUSSION

In this section, specific maneuvers from the phase of the mission covered here are discussed. Maneuvers that were unique or stood out in some way are highlighted.

OTM-438 and OTM-444: Last Large Main Engine Burns

At the time it was performed, OTM-438 was one of the largest remaining main engine maneuvers, with a deterministic ΔV of 6.85 m/s. Given the size of the maneuver and the propellant left on the spacecraft, there was estimated to be a 1.2% chance that Cassini would run out of propellant before completion of the maneuver. To add to the risk, without performing the maneuver, Cassini was on a trajectory that would impact Titan at the time of the upcoming encounter (T116), and at least 85%

Table 3: Maneuver Performance per Encounter (E22 – T125)

Encounter Span	Ref. Traj. Det. ΔV (m/s)	Predicted ΔV Statistics Mean (m/s)	1-σ (m/s)	90%* (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Navigation ΔV Cost† (m/s)
E22–T115	3.044	3.055	0.073	3.143	3.022	3.021	−0.023
T115–T116	6.850	6.979	0.092	7.108	6.863	6.860	0.011
T116–T117	0.737	1.175	0.338	1.636	1.345	1.338	0.600
T117–T118	7.961	8.227	0.165	8.457	8.083	8.087	0.126
T118–T119	1.758	2.258	0.301	2.673	1.951	1.946	0.188
T119–T120	0.049	0.312	0.182	0.562	0.577	0.578	0.530
T120–T121	2.107	2.370	0.157	2.574	2.329	2.317	0.210
T121–T122	0.851	1.260	0.275	1.632	0.978	0.978	0.128
T122–T123‡	0.058	0.467	0.295	0.879	0.080	*0.080*	*0.021*
T123–T124‡	0.020	0.264	0.209	0.560	0.189	*0.191*	*0.171*
T124–T125‡	0.105	0.430	0.261	0.782	0.143	*0.142*	*0.037*

* Total ΔV in encounter span will be less than or equal to this value with a 90% confidence level.
† Navigation ΔV cost = reconstructed ΔV − reference trajectory deterministic ΔV. Note, the computed navigation costs are based on the raw numbers to avoid round-off errors.
‡ Reported navigation cost is based on preliminary orbit determination estimates.

Table 4: Average Navigation ΔV Cost per Encounter, computed through 2016.

Mission	Flyby Span	Number of Flybys	Navigation ΔV Cost Mean (m/s)	Std. Dev. (m/s)
Prime (7/2004 – 9/2008)	Ta – E4	54	0.325	0.594
Equinox (9/2008 – 9/2010)	E5 – T72	36	0.447	0.978
Solstice (9/2010 – 11/2016)	T73 – T125	69	0.132	0.145

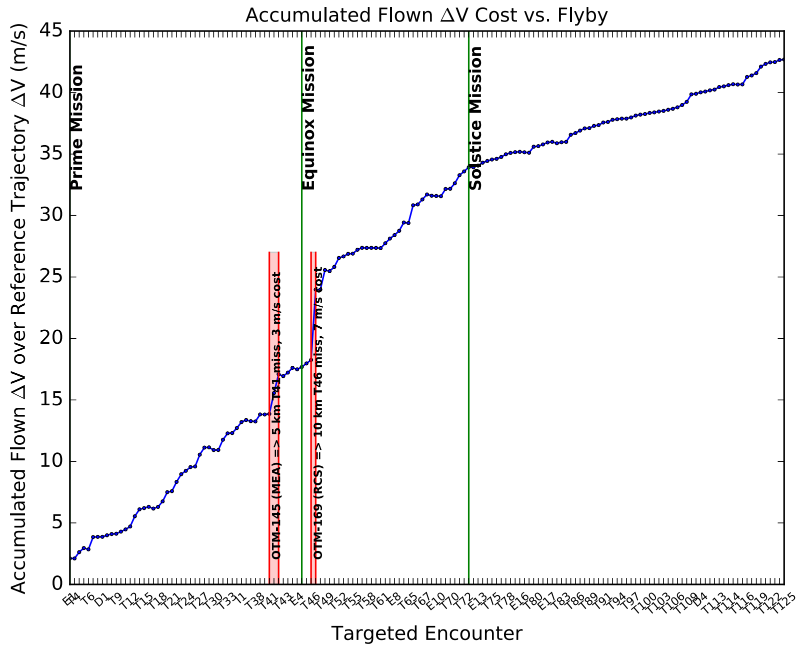


Figure 3: The accumulated navigation cost for the entire Cassini mission. The more shallow slope during the Solstice Mission reflects an approach that favors saving ΔV.

of the maneuver would need to be completed to move off the impactor trajectory. A plot of the effect of OTM-438 on the Titan B-plane crossing point is shown in Figure 5.

Because of the risk of propellant depletion, a backup plan was put in place to complete the trajectory correction with up to two maneuvers using the RCS system (which is not low on propellant) in the event that the primary maneuver did not complete. The RCS system is constrained to perform not more than 4 m/s of ΔV at a time, so two maneuvers would be needed if more than 4 m/s was left to perform. The two maneuvers would be designed together to achieve the target aim point while minimizing ΔV with an optimization strategy. While a backup is planned during every maneuver (generally occurring one day later), those are intended for cases where the prime maneuver could not be executed because of a problem communicating with the spacecraft (e.g. the ground station malfunctions or is subject to severe weather). The backup maneuvers are designed with the same propulsion system as the prime maneuvers, which is why the contingency was a special case using the RCS system over two maneuvers. Fortunately, the prime maneuver executed without issue.

This situation repeated itself with OTM-444, which at 7.95 m/s was the largest remaining main engine burn in the mission. Occurring on March 25, 2016, this maneuver had an estimated 6.0% chance of propellant depletion before the burn finished. As with OTM-438, if the burn cut out before providing the required ΔV, Cassini would have likely been left on a trajectory impacting Titan, and up to two RCS burns would be required to recover. Happily, the prime maneuver once again executed as planned and no contingency burns were required.

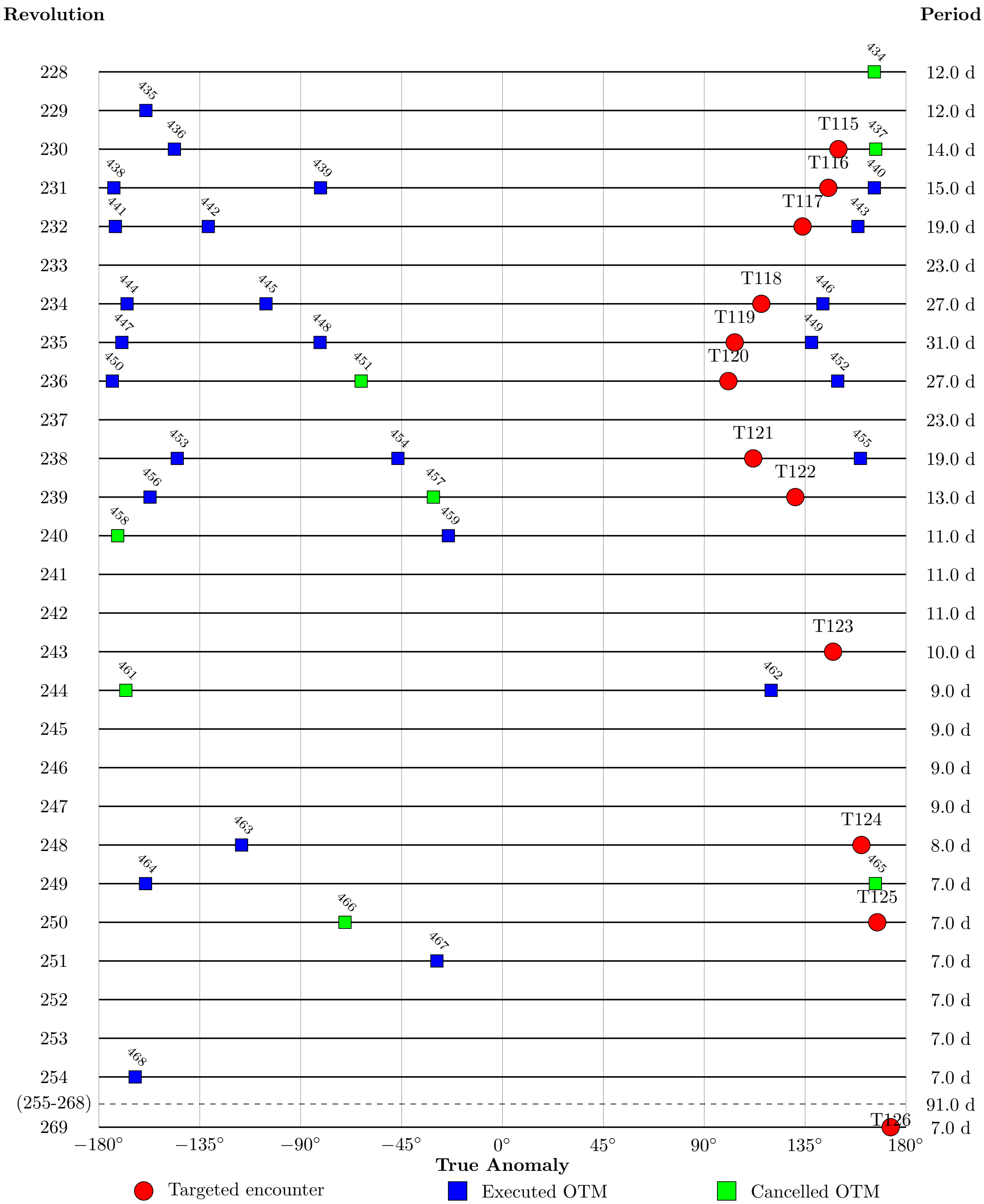


Figure 4: Titan-115 through Titan-125 Orbital Events. Each line represents one revolution of Cassini around Saturn, with the horizontal position of the event indicating the true anomaly at which it occurred. The period of each revolution is noted along the right-hand side.

OTM-443: Enceladus Plume Stellar Occultation

OTM-443 was a unique maneuver because it was designed to put Cassini at a specific position in space at a specific time such that a star (Alnilam, the middle star in Orion's Belt) would pass behind

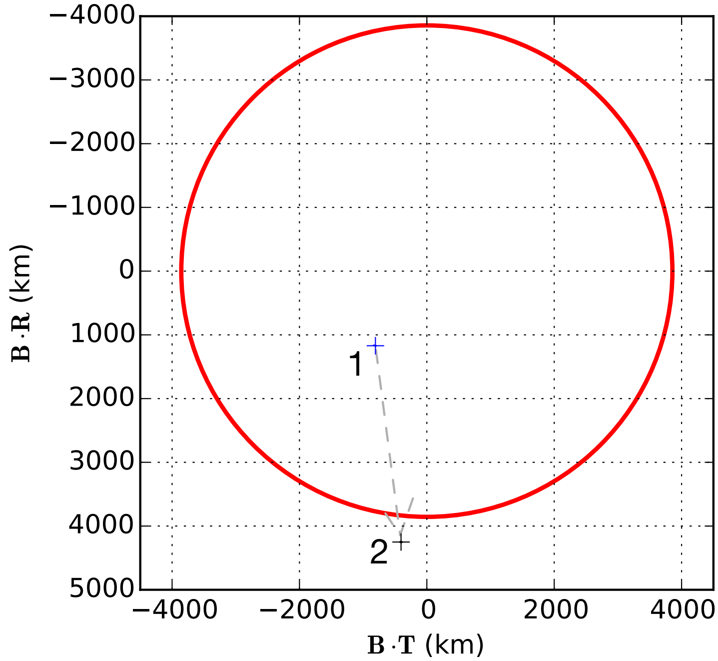
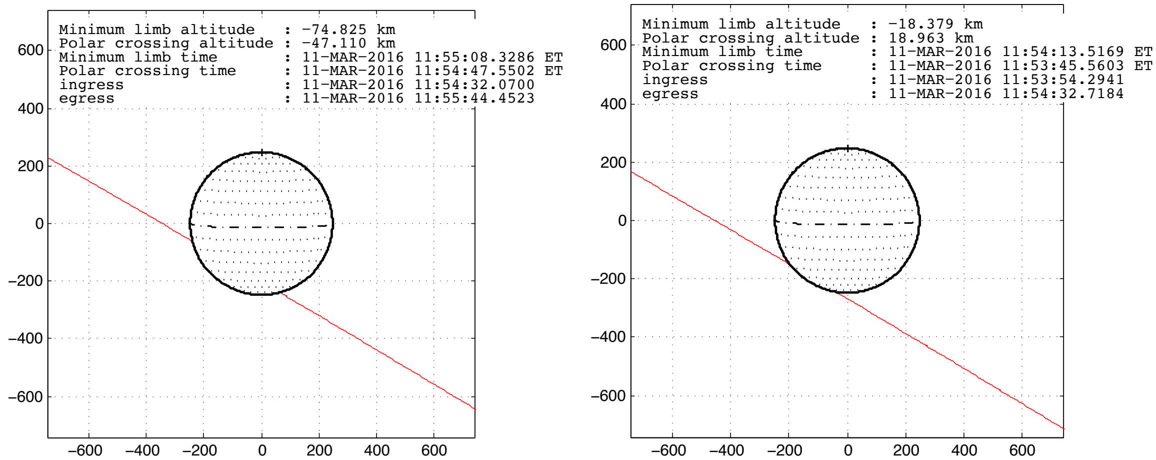


Figure 5: Performing OTM-438 would move Cassini's Titan B-plane crossing from point 1 (impacting Titan) to point 2.

the plumes of Enceladus from Cassini's point of view. To accomplish this, the maneuver would be designed to directly target the Cartesian state necessary for the occultation instead of the usual B-plane targets. This orientation would allow Cassini's ultraviolet spectrometer (UVIS) to collect data that could provide insight into the chemicals contained in the plumes.

For the occultation to be a success, the star needed to appear to pass directly over the south pole of Enceladus from Cassini's point of view. Because Enceladus' plumes occur over the south pole, this geometry would ensure that the starlight would pass through the plumes before reaching Cassini. As shown in Figure 6, if OTM-443 was not performed, the star would pass behind Enceladus too early, missing the plumes. Performing the maneuver lowered the apparent trajectory of the star such that it was occulted by the plumes.

The occultation event called for a relatively high accuracy in the position of Cassini at the prescribed time. However, leading up to the maneuver, it was determined that, given the uncertainty in the spacecraft state, OTM-443 may not have been able to place Cassini at the right location. To solve this problem, the backup maneuver, OTM-443 BU, would be used instead. The backup maneuver would take place one day later than the prime maneuver. This delay would allow for more tracking data, refining the estimate of Cassini's orbit and allowing for a more accurate maneuver design. OTM-443 BU was executed 20 February, 2016 with a ΔV of 69 mm/s using the RCS thrusters. The occultation event itself occurred on 11 March, 2016, and was deemed a success by the mission scientists.



(a) Without OTM-443 BU.

(b) With OTM-443 BU

Figure 6: These figures show the apparent trajectory (straight red line) of the star Alnilam in the view from Cassini fixed on Enceladus. With the maneuver, the star would appear to pass over the south pole, ensuring it would be occulted by the plume.

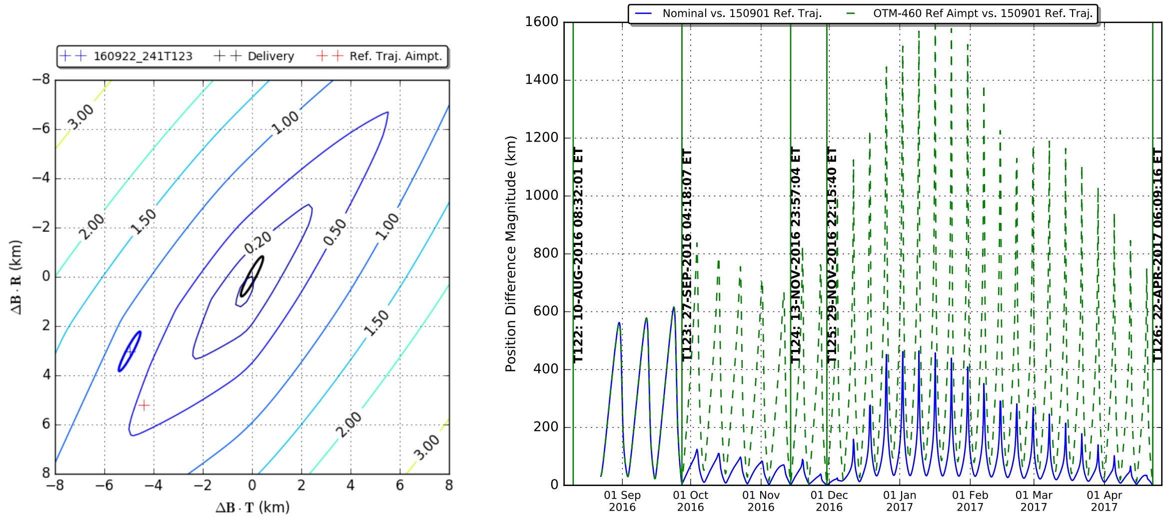
OTM-460: Aim Point Shift at T123

OTM-460 was the approach maneuver leading up to the T123 encounter. While designing the two prior maneuvers, it was seen that shifting the B-plane aim point at T123 could result in saving ΔV while also reducing the deviations from the reference trajectory between T123 and T126. Reducing the deviations at OTM-460 was important because doing so later, for example at OTM-467, was shown to be more costly. In Figure 7a, contours of the downstream ΔV cost are plotted in the T123 B-plane along with the OD solution at the time, the aim point from the reference trajectory, and the new shifted aim point. These plots are produced using a grid search that estimates the downstream cost of different B-plane aim points with a linearized maneuver design model. Examining these cost contour plots before a flyby allows the maneuver team to determine if there is a different aim point that can reduce costs. While the reference aim point is usually at or very near the lowest cost aim point, there are occasionally chances to save cost by shifting it, as was the case with T123. Shifting the aim point at T123 was estimated to save a total of 0.34 m/s.

In Figure 7b, the predicted deviation from the reference trajectory is shown for the cases both with and without the shift of aim point. The trajectory resulting from the shifted aim point was found to be much closer to the reference trajectory than if the reference aim point was used.

OTM-462: Costly Backup

During the design of OTM-462, it was found that the backup maneuver, OTM-462 BU, would be very costly to implement should it be necessary. While the prime maneuver would be a 0.17 m/s burn—implementable with the RCS system—the backup was almost three times the size at 0.5 m/s and would have to use the main engine. The backup maneuver was scheduled only a day after the prime, and both maneuvers would occur over five weeks before the encounter the targeted encounter (T124). However, the one day of difference meant that the location of the backup maneuver would be separated from the encounter location by 1448° of rotation through the orbit—almost exactly 4



(a) The new aim point in the black ellipse is shown to be less costly than the aim point from the reference trajectory, indicated by the red cross mark. The contour lines show the ΔV cost of the downstream maneuvers in meters per second.

(b) Shifting the aim point at T123 resulted in a trajectory much closer to the reference trajectory. The blue line represents the trajectory with the shifted aim point while the dashed green line is the trajectory with the reference aim point.

Figure 7: Shifting the aim point at T123 saved both ΔV and reduced deviations.

revolutions (1440°). This geometry is very unfavorable for a maneuver, and results in maneuvers that are much larger than they otherwise need to be.

OTM-463: Aim Point and TCA Bias

OTM-463 was the approach maneuver leading up to the Titan-124 encounter. As with OTM-460, it was found that shifting the B-plane aim point again at T124 would yield propellant savings in the downstream maneuvers. A contour plot showing the cost savings in the T124 B-plane is shown in Figure 8. However, unlike OTM-460, OTM-463 was too small to implement at 13.2 mm/s. Therefore, in addition to saving cost with an aim point shift, the time of closest approach to Titan for the T124 encounter was given a -0.2 second bias. Adding this time bias increased the size of the maneuver to 18.4 mm/s, making it implementable with Cassini's RCS propulsion system. This maneuver marked the first time in the mission that both an aim point shift and TCA bias were added to the same maneuver.

First time events

During this portion of the mission, there were several events that happened for the first time during the Solstice Mission. OTM-451, the approach maneuver for T120 was canceled. This marked the first time during the Solstice Mission that an approach maneuver was canceled for a low-altitude Titan flyby. Such flybys typically yield a cost penalty for relatively small misses, meaning the approach maneuver is usually required to avoid downstream costs. In addition, OTM-448 and OTM-459 were performed on the backup window because they needed less ΔV than the prime maneuvers. Before OTM-448, a backup maneuver had never been performed for the sole purpose of saving

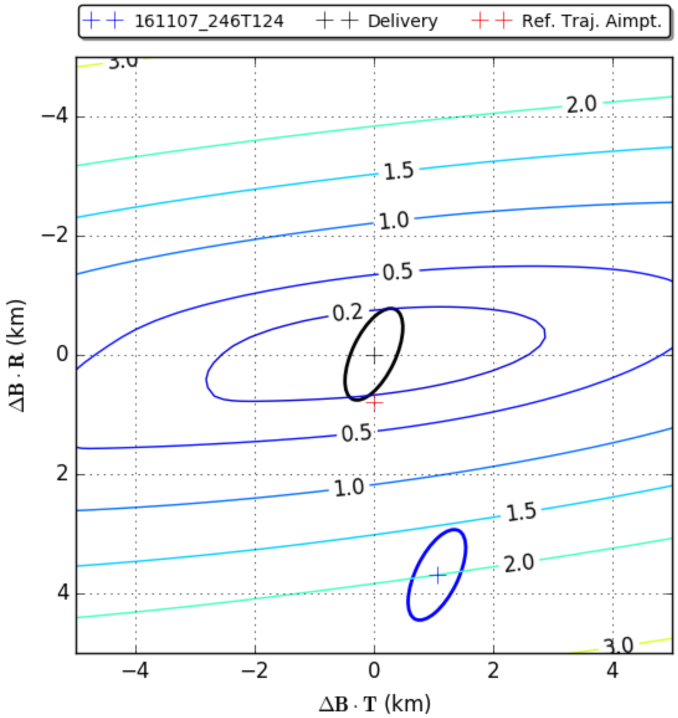


Figure 8: The new aim point in the black ellipse is shown to be less costly than the aim point from the reference trajectory, indicated by the red cross mark. The contour lines show the difference in ΔV, in m/s, over the shifted aim point solution.

propellant. Performing OTM-448 BU saved 40 mm/s over the prime, while OTM-459 saved 74 mm/s.

CONCLUSION AND LOOKING AHEAD

During the phase of the mission discussed here, Cassini's orbit went from near equatorial to an inclination of over 60° using eleven Titan gravity assists and 25 maneuvers. Despite being in operation for over 19 years, no significant incidents or failures occurred during this time. At the completion of this phase, Cassini is left with only nine months to go before it plunges into Saturn. There are five planned maneuvers left in the mission: two prior to T126 and three during the Proximal Orbits Phase. As of January 2017, the current best estimate indicates that there is enough bi-propellant left for 3 m/s of ΔV on the main engine, and there is enough hydrazine left for 20 m/s of ΔV with the RCS engines.

Cassini is now in a phase of the mission known as the F-ring orbits, which is so named because the spacecraft passes just outside the edge of Saturn's F-ring with a period of 7.2 days. Following the final targeted Titan flyby in April (T126) Cassini will "jump" across the rings in an orbit that takes it through a 3000 km wide gap between the cloud-tops of Saturn and the inner-most ring. These final orbits have been named the Proximal Orbits, and have a period of 6.5 days. The proximal orbits phase will allow Cassini to take its best ever gravity science measurements of Saturn and its rings. Finally, on September 15, 2017, Cassini will plunge into the depths of Saturn, marking the end of this historic mission.

APPENDIX

Additional Maneuver Data

In Table 5, additional information about each maneuver is listed. Roll and yaw angles are the angles through which the spacecraft turns to get from an Earth-pointed orientation to the direction required for the maneuver. Central angle is the total angle swept out between the maneuver and the point targeted by the maneuver. When the central angle is a multiple of π, a maneuver is unable to fully control the target point and tends to become very large.

Table 5: Maneuver Designs (OTMs 434–466). *Data from executed maneuvers are shaded in blue, and data from main engine maneuver designs are indicated in bold.*

	Prime Maneuver Window						Backup Maneuver Window					
OTM	True Anomaly (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)	Burn Time (sec)	True Anomaly (deg)	Central Angle (deg)	ΔV Mag. (m/s)	Roll Angle (deg)	Yaw Angle (deg)	Burn Time (sec)
434	165.82	707.93	0.0021	93.26	−102.63	2.56	171.13	702.61	0.0028	104.04	−93.14	3.28
435	**−159.03**	**672.78**	**2.9863**	**−171.42**	**−66.28**	**17.01**	**−148.20**	**661.96**	**3.4660**	**−169.61**	**−65.91**	**19.75**
436	−146.30	299.66	0.0362	−101.39	−116.17	32.34	−106.26	259.62	0.0649	−139.72	−148.13	62.38
437	166.46	338.87	0.0006	58.46	−161.59	0.89	171.01	334.32	0.0003	−175.80	−171.38	0.61
438	**−173.33**	**318.66**	**6.8471**	**−134.65**	**−56.24**	**38.74**	**−169.13**	**314.46**	**6.6518**	**−134.65**	**−56.71**	**37.63**
439*	−135.84	281.18	0.0160	−98.39	−134.45	11.01	−81.16	226.51	0.0158	92.74	−166.61	10.88
440	**165.87**	**337.50**	**0.5826**	**−27.45**	**−77.45**	**3.44**	**170.68**	**332.69**	**0.7725**	**−43.82**	**−68.46**	**4.56**
441	**−172.63**	**316.01**	**0.7469**	**−146.34**	**−46.71**	**4.35**	**−168.12**	**311.50**	**0.7193**	**−147.16**	**−48.19**	**4.19**
442	−131.20	274.58	0.0153	99.02	−36.66	10.32	−65.52	208.90	0.0326	−121.11	−21.62	28.44
443	153.41	693.16	0.0585	11.31	−90.04	55.69	158.52	688.06	0.0688	−11.38	−85.39	66.52
444	**−167.49**	**294.00**	**7.9518**	**−139.91**	**−39.51**	**44.94**	**−163.76**	**290.27**	**8.0487**	**−143.98**	**−38.79**	**45.49**
445	−105.47	232.01	0.0625	−61.95	−157.32	59.53	−18.07	144.58	0.1475	−134.14	−121.12	147.44
446	142.90	328.74	0.1668	−54.43	−108.19	167.57	148.50	323.14	0.1664	−60.56	−110.25	167.09
447	**−169.76**	**281.45**	**1.7674**	**−68.18**	**−43.92**	**10.10**	**−166.95**	**278.64**	**1.7552**	**−70.49**	**−43.18**	**10.03**
448	−81.35	193.02	0.0619	−38.73	−83.96	59.26	−0.41	112.05	0.0172	145.16	−107.50	12.43
449	**137.83**	**324.86**	**0.5512**	**−83.38**	**−80.09**	**3.25**	**144.22**	**318.48**	**0.6063**	**−82.02**	**−87.77**	**3.57**
450	−173.98	276.71	0.0261	93.4	−43.22	21.78	−170.98	273.72	0.0295	93.30	−41.05	25.36
451	−63.01	165.74	0.0163	−9.97	−87.91	11.46	8.69	94.03	0.0172	−37.29	−124.04	12.50
452	**149.50**	**674.44**	**0.2542**	**−95.50**	**−127.44**	**1.51**	**155.95**	**668.00**	**0.2757**	**−88.00**	**−129.55**	**1.64**
453	**−144.97**	**248.97**	**2.0250**	**90.97**	**−106.73**	**11.55**	**−136.58**	**240.57**	**2.2013**	**89.06**	**−115.62**	**12.56**
454	−46.61	150.52	0.0501	152.41	−108.31	47.31	23.56	80.33	0.0772	134.29	−74.88	75.88
455	159.64	320.94	0.1839	2.20	−32.21	188.56	168.61	311.99	0.2518	28.37	−23.82	260.07
456	**−157.19**	**277.78**	**0.7940**	**139.82**	**−48.47**	**4.60**	**−146.67**	**267.25**	**0.8179**	**133.35**	**−38.23**	**4.73**
457	−30.76	151.33	0.0202	−156.20	−75.26	15.68	49.50	71.07	0.0141	174.24	−97.22	9.15
458	−171.60	1390.59	0.0307	−102.42	−112.09	26.86	−160.17	1379.16	0.1355	−77.64	−138.47	137.13
459	−24.07	1243.06	0.1080	169.51	−76.27	108.28	76.73	1142.27	0.0554	142.50	−127.74	52.87
460	−97.27	236.30	0.0245	−81.55	−24.19	20.18	78.10	60.93	0.0257	51.89	−31.97	21.45
461	−167.98	1761.67	0.1098	−106.25	−77.45	110.68	−154.41	1748.11	0.1957	−93.12	−110.11	201.33
462	119.81	1473.90	0.1710	5.48	−141.72	175.24	**145.41**	**1448.30**	**0.5028**	**55.11**	**−148.20**	**2.98**
463*	−116.34	270.08	0.0184	149.84	−146.03	13.84	−25.95	179.70	0.1087	−148.20	−94.82	109.77
464	−159.18	683.34	0.1427	−74.24	−111.06	145.39	−139.90	664.06	0.0704	−54.61	−128.39	69.03
465	166.32	357.86	0.0241	−140.03	−12.72	19.96	177.52	346.67	0.0031	−148.56	−16.17	3.64
466	90.33	73.93	0.0033	73.94	−100.38	3.88	121.17	43.06	0.0035	75.37	−115.83	4.10

* Prime and backup maneuver designs required time-of-flight modifications to make implementable.

ACKNOWLEDGEMENT

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REFERENCES

[1] T. D. Goodson, D. L. Gray, Y. Hahn, and F. Peralta, "Cassini Maneuver Experience: Launch and Early Cruise," *AIAA Guidance, Navigation, & Control Conference,* AIAA Paper 98-4224, Boston, MA, August 10–12, 1998.

[2] T. D. Goodson, D. L. Gray, Y. Hahn, and F. Peralta, "Cassini Maneuver Experience: Finishing Inner Cruise," *AAS/AIAA Space Flight Mechanics Meeting,* AAS Paper 00-167, Clearwater, FL, January 23–26, 2000.

[3] T. D. Goodson, B. B. Buffington, Y. Hahn, N. J. Strange, S. V. Wagner, and M. C. Wong, "Cassini-Huygens Maneuver Experience: Cruise and Arrival at Saturn," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 05-286, Lake Tahoe, CA, August 7–11, 2005.

[4] S. V. Wagner, B. B. Buffington, T. D. Goodson, Y. Hahn, N. J. Strange, and M. C. Wong, "Cassini-Huygens Maneuver Experience: First Year of Saturn Tour," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 05-287, Lake Tahoe, CA, August 7–11, 2005.

[5] S. V. Wagner, E. M. Gist, T. D. Goodson, Y. Hahn, P. W. Stumpf, and P. N. Williams, "Cassini-Huygens Maneuver Experience: Second Year of Saturn Tour," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2006-6663, Keystone, CO, August 21–24, 2006.

[6] P. N. Williams, E. M. Gist, T. D. Goodson, Y. Hahn, P. W. Stumpf, and S. V. Wagner, "Cassini-Huygens Maneuver Experience: Third Year of Saturn Tour," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 07-254, Mackinac Island, MI, August 19–23, 2007.

[7] T. D. Goodson, C. G. Ballard, E. M. Gist, Y. Hahn, P. W. Stumpf, S. V. Wagner, and P. N. Williams, "Cassini Maneuver Experience: Ending the Prime Mission," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2008-6751, Honolulu, HI, August 18–21, 2008.

[8] E. M. Gist, C. G. Ballard, Y. Hahn, P. W. Stumpf, S. V. Wagner, and P. N. Williams, "Cassini-Huygens Maneuver Experience: First Year of the Equinox Mission," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 09-349, Pittsburgh, PA, August 9–13, 2009.

[9] C. G. Ballard, J. Arrieta, Y. Hahn, P. W. Stumpf, S. V. Wagner, and P. N. Williams, "Cassini Maneuver Experience: Ending the Equinox Mission," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2010-8257, Toronto, Canada, August 2–5, 2010.

[10] S. V. Wagner, J. Arrieta, C. G. Ballard, Y. Hahn, P. W. Stumpf, and P. N. Valerino, "Cassini Solstice Mission Maneuver Experience: Year One," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper 11-528, Girdwood, AK, July 31–August 4, 2011.

[11] J. Arrieta, C. G. Ballard, Y. Hahn, P. W. Stumpf, P. N. Valerino, and S. V. Wagner, "Cassini Solstice Mission Maneuver Experience: Year Two," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA-2012-4433, Minneapolis, MN, August 13–16, 2012.

[12] S. V. Wagner, J. Arrieta, Y. Hahn, P. W. Stumpf, P. N. Valerino, and M. C. Wong, "Cassini Solstice Mission Maneuver Experience: Year Three," *AAS/AIAA Astrodynamics Specialist Conference,* AAS 13-717, Hilton Head, SC, August 11–15, 2013.

[13] M. Vaquero, Y. Hahn, P. W. Stumpf, P. N. Valerino, S. V. Wagner, and M. C. Wong, "Cassini Maneuver Experience for the Fourth Year of the Solstice Mission," *AAS/AIAA Astrodynamics Specialist Conference,* AAS 14-4348, San Diego, CA, August 4–7, 2014.

[14] S. Hernandez, S. V. Wagner, M. Vaquero, Y. Hahn, P. N. Valerino, F. E. Laipert, M. C. Wong, and P. W. Stumpf, "Cassini Maneuver Experience Through the Last Icy Satellite Targeted Flybys of the Mission," *26th AAS/AIAA Space Flight Mechanics Meeting*, Napa, CA, February 14–18 2016.

[15] B. Buffington, J. Smith, A. Petropoulos, F. Pelletier, and J. Jones, "Proposed End-of-Mission for the Cassini Spacecraft: Inner D Ring Ballistic Saturn Impact," *International Astronautical Congress,* IAC-10-C1.9.2, Prague, Czech Republic, 27 September–1 October 2010.

[16] J. Smith and B. Buffington, "Overview of the Cassini Solstice Mission Trajectory," *AAS/AIAA Astrodynamics Specialist Conference,* AAS 09-351, Pittsburgh, PA, August 9–13, 2009.